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Space Transportation Operations Cost Modeling and the Architectural Assessment Tool - Enhanced

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[1]ABSTRACT

This paper presents an approach to space transportation operations cost modeling which synergistically combines knowledge capture with data. The functioning model derived from this approach will be described. As with any model, the goal is to gain insights into systems which do not yet exist, in this case advanced reusable launch vehicle (RLV) concepts. These insights include the interaction of a launch vehicle with its ground infrastructure, hereafter referred to as the spaceport. These interactions include the need, or not, for multiple facilities and ground support equipment (GSE), costs resulting from acquiring facilities and GSE, time cycles and costs resulting from flight vehicle design and operational decisions, and costs per pound for a resulting flight rate. These interactions also include the variation of all these factors when a concept strives to meet a desired demand, or yearly space-lift requirement. The significance of this approach to space transportation cost modeling, particularly operations, will be shown in relation to the current state of operations cost modeling. Further, the potential use of such an approach in multitudes of decision making opportunities today, ranging from technology investment to business decisions, will be outlined. A work in progress for the extension of this approach to a broad range of space transportation systems will also be described. The latter is called the Vision Spaceport project.

Further, work in the application of this model to both near and far term studies will be reviewed. In the near term, NASA has recently completed a Space Transportation Architecture Study (STAS) for 1999. This study had as it's objectives determining: (1) should the Space Shuttle system be replaced, (2) if so, when the replacement should take place and how the transition should be implemented, and (3) if not, what is the upgrade strategy to continue safe and affordable flights of the Space Shuttle. The use of the model and approach presented here, applied in support of this study, will be summarized for this sample set of cases.

In the far term, the application of this tool to the Space Solar Power (SSP) study will also be summarized. The SSP study has, as one of its objectives, a definition of Earth-to-Orbit concepts that are capable of meeting the economic challenges of the broader SSP project. This includes defining concepts capable of hundreds of flights per year per vehicle, at costs in the range of 100's of dollars per kilogram. The types of concepts derived and the characteristics of these, as well as implications for spaceport development, and overall flight and ground technology development will be briefly summarized.

INTRODUCTION

The potential uses of space have not been fully achieved given the high costs of reaching that frontier. These high costs arise not only from the one-time investments required to design and manufacture vehicles, but also from the recurring systems operation and maintenance. As an example, given the Space Shuttle's planned life, most of the multi-million dollar cost required for a single Shuttle mission is directly linked to operational costs. The lesser part (in the hypothetical scenario that it was a commercial venture that had to payback investment money) would be related to the development and vehicle acquisition costs, amortized over the total number of Shuttle missions.

Assessment of the operational characteristics and associated costs of planned or operational space transportation systems have been, up until recently, a neglected topic. In the traditional space transportation system design approach, the process focused on flight parameters, for example the engine performance and specific impulse, while it ignored the operational issues, such as the processes required to maintain, service, and integrate a vehicle or fleet of vehicles. This is now changing and there are several efforts underway to improve the design process by including operations assessment during the early concept definition process.

This paper describes a modeling methodology that supports the analysis of operational requirements for vehicle concepts. The modeling methodology combines existing data and expert knowledge to provide an operational assessment of concept vehicles. The paper first describes the current situation in terms of existing operational models and data. The need for operational insights is explained next, followed by a description of the model approach. The very important concept of single vehicle productivity is explained, followed by a summary of cornerstone concepts, and lastly, conclusions and future work.

CURRENT SITUATION - LACK OF APPROPRIATE MODELS AND DATA

NASA document NSTS 5300.4 (1D-2) "Safety, Reliability, Maintainability and Quality Provisions for the Space Shuttle Program"[6] has outlined since the 1970's those provisions for the collection of crucial data from the operation of the Space Shuttle fleet. This data includes maintainability parameters such as mean time to repair, cost breakdowns traceable to flight sub-systems, or ground equipment, and overall resource parameters. Separately, operations contracts have routinely deleted the applicable sections. To quote from the document and from separate contract revisions:

> *1D401 PROGRAM ELEMENTS*
> *(1.) Maintainability parameters. Establish measurable parameters…mean time to repair, fault detection/isolation capability and maintenance staff-hours per turnaround/reaction time requirements, … maintenance resources and other factors.*
> *(2.) Maintainability Allocation. Budget parameters to system/subsystem/equipment and establish criteria to meet targets.*
>
> *Shuttle Processing Contract (SPC) revision: Paragraphs 1D401 (1.0) (2.0) (5.0) and (6.0) delete entirely.*

The previous deletion was approved as a cost savings (avoiding the investment) and it is only recently that some efforts are attempting to institute systems for such data gathering.

This single deletion explains in large part the situation that has developed in space transportation operations cost modeling to this day. The lack of hard data, such as maintainability parameters, cost data down to sub-systems (main propulsion, power, controls, etc) and most reliability/dependability data has severely hampered the state of operations cost modeling for future reusable space transportation systems. That the Shuttle fleet is the *only semi-reusable, operational, crew capable,* access to space makes the situation even more severe.

This undesirable situation, affecting understanding the operation of reusable space transportation systems, has not gone without notice by multiple parties throughout the years:

"However the lack of a suitable compilation of the reliability and maintainability (R&M) history of the Orbiter has been a major hindrance in benefiting from that experience"[5]

Morris, W.D., White, N.H. and Dr. Ebeling, C.E., 1996

"Finding 4: If the federal government wishes to invest in new operations technologies, it should have clear long-term goals and a well defined plan for developing and incorporating new technologies in space transportation operations. Such a plan must be buttressed by data from new and more reliable cost models."[10]

-U.S. Congress, Office of Technology Assessment, 1988

Within the context of this situation, lack of data, a review of current models for space transportation systems is in order. Common characteristics among cost models are shown in Table 1.0.

Cost Model	Common Characteristics
• *AMCM, the Advanced Mission Cost Model* • *SVLCM, the Spacecraft/ Vehicle Level Cost Model, derived from NAFCOM* • *NAFCOM, the NASA/Air Force Cost Model* • *PRICE-H* • *SEER-H* • *TRANSCOST*	• Up Front Costs - Design, Development, Test and Engineering (DDT&E) Costs • Weight, size and overall complexity based • Design experience, manufacturing complexity, size and organizational standards as drivers • Parametric type analysis based on existing
• *COMET/OCM, the Conceptual Operations Manpower Estimating Tool/ Operations Cost Model*	• Operations, Space Transportation • Based on major complexities, but with flight rate as an input • Flight rate as input • Parametric type analysis based on existing

Table 1.0

Most models have the particular trait of being heavily driven by complexity, size and weight factors[3]. While some models also address operations[4,2] multiple characteristics, from a user perspective, may be desired of any operations cost model which are not currently available. It is within this context that the model which is the subject of this paper was developed.

OPERATIONS INSIGHT - WHY THE NEED?

For a reusable launch system the operations costs may represent 70% or more of the total life cycle cost. Further, the number and scope of decisions being made by government agencies such as NASA and Department of Defense, and by industry and entrepreneurs alike, indicates that the need exists for clarity in understanding today's design decisions and tomorrow's operational consequences. In this light, cost modeling efforts have been newly emphasized within NASA as witnessed by the Space Operations Cost Model (SOCM) efforts currently underway at Marshall Space Flight Center (MSFC) in conjunction with Kennedy Space Center (KSC) and Langley Research Center (LaRC).

These observations are specific to the <u>operation</u> of a reusable space transportation system. For a reusable launch system the contribution of cost from the operation of the system, across the entire life cycle, is the key determinant of a broader factor - affordability.

Multiple studies[1] have shown the need for drastic reductions in the cost of access to space, down to one to two orders of magnitude less than current costs. This would be hundreds of dollars per pound at high flight rates, hundreds of flights per vehicle per year. It is not until then that industry revenue as a whole would begin to demonstrate marked elasticity, creating new markets and likely spurring unprecedented economic growth.

Consider that launch vehicles represent only a portion, and in some cases a small portion of the space business economy, as compared to the business of providing bits and bytes to consumers, which could be in the hundreds of billions of dollars within a few years. It becomes apparent that, as one workshop[7] on the subject recently concluded "space transportation - is the bottleneck that currently constrains space enterprises to the imaginable."

COST MODEL OBJECTIVES

To overcome and address the state of affairs outlined previously in space transportation operations cost modeling, a clean sheet approach was undertaken. Goals considered for this model are outlined in Table 2.0.

Space Transportation Operations Cost Model Characteristics	Rationale
1. Ability to extend beyond existing systems	• Allow definition of innovative concepts that "leave the line" of existing technologies
2. Ability to overcome data shortcomings	• Data unavailable for flight subsystems relationships to ground infrastructure for reusable space transportation systems
3. Give insight down to facilities, their functions, and to the efficiency of the flight to ground interaction	• Existing models provide only top level insight
4. Avoid flight rate or cycle times as inputs	• Avoid circular logic confirming in outputs assumptions already made
5. Provide alternate feedback mechanisms down to sub-systems levels to flight vehicle designers/concept developers	• Existing models emphasis on weight reductions, size reductions, and top-level complexity factors limit useful information for improving designs for operations

Table 2.0

MODEL APPROACH AND STRUCTURE

The model described here is the Architectural Assessment Tool - enhanced (AATe). The knowledge based approach, which is synergistically combined with existing data, is heavily traceable to the work of a national team called the Space Propulsion Synergy Team (SPST). This work was performed in support of the NASA Highly Reusable Space Transportation (HRST) Study. In this work[11], a knowledge capture process of a broad government/industry team resulted in the documentation of multiple, prioritized, factors as recurring and non-recurring drivers affecting reusable space transportation systems[8].

It is the recurring factors identified previously which form a key component of the knowledge base used here. Further work expanded and built on spaceport operations. The result was a series of modules and a model definition[9] encompassing a functional spaceport. This is shown in Figure 1.0.

To build on this previous work a means was needed to connect the knowledge capture to what data could be determined in a useful breakdown.

The means by which a knowledge base is turned into a series of factors, which can be manipulated and correlated to data, and to the desired set of model outputs, is by use of a function referred to as the multi-attribute utility function. This function captures not only the relation of a particular choice to the outputs, but also the strength, or importance of the broader context which is being addressed. In this way the model will behave with some similarity to the thought processes an expert, or an organization of experts, may undergo when performing a cost assessment.

This function is defined as:

$F(M) = SUM_{i=1 \ldots I, j=1 \ldots Ji} (X_{ij} * S_{iM} / (SUM_{y=1 \ldots I} S_{yM}))$	I = Number of design/assessment questions J_i = Number of options for design/assessment question i X_{ij} = Value of option j for design/assessment question i S_{iM} = Strength of relation, design/assessment question i to module M F(M) = Score for Module/facility function M (12 in total)

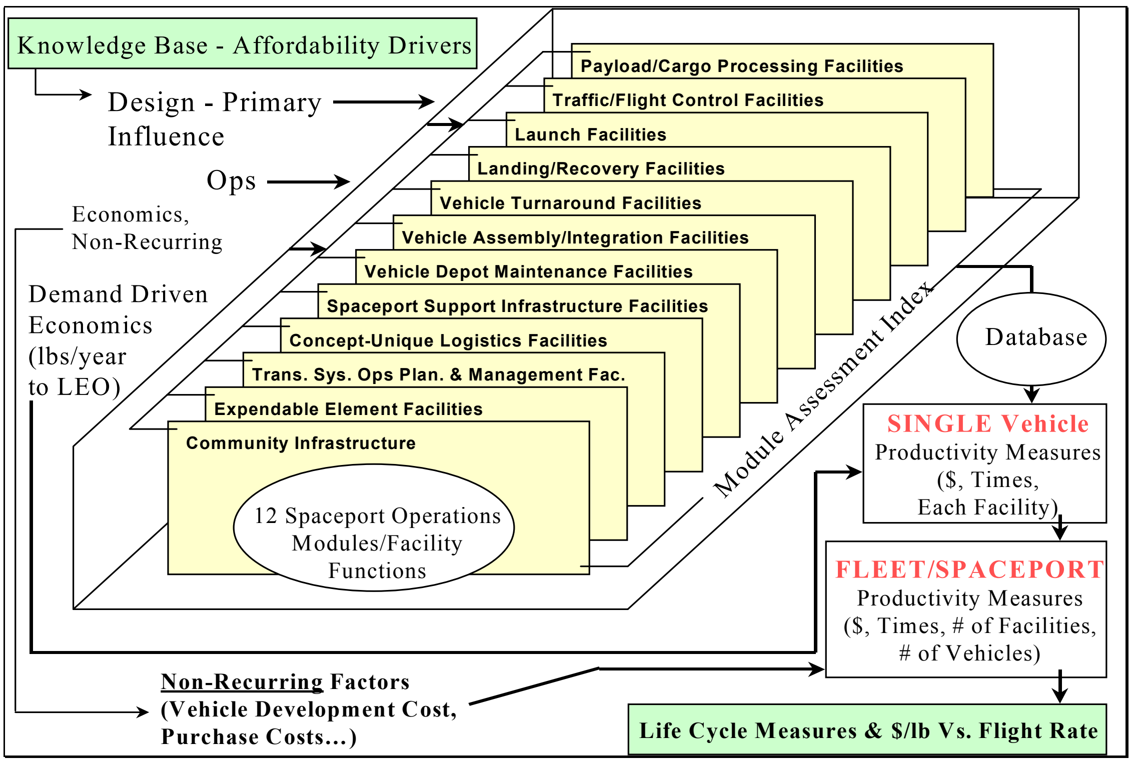

FIGURE 1.0 Spaceport Model Definition and AATe Basic Structure

The multi-attribute utility function is used here in its additive form. As used in this simpler model the questions are exclusionary, with no branching required. Put simply, in the additive form all flight vehicle design/operational choices contribute or subtract from spaceport productivity. In a more complex model, a multiplicative form, or more complex coding, could be used to refine estimates, such as where a design choice positively affecting operations has limited return due to another choice which limits the amount of benefit.

MODEL PROCESS

As the concept is inputted, by the user answering a set of questions for the concept being assessed (Figure 2.0), the multi-attribute utility function values are calculated. The questions are based on the knowledge capture of costs drivers previously outlined. The Module Assessment Index (Figure 1.0), calculated for each module with the previously defined function, is used as a correlation to a set of data. The data set includes a baseline, Shuttle in this case, as well as a series of extrapolations, which are higher or lower costs and cycle times.

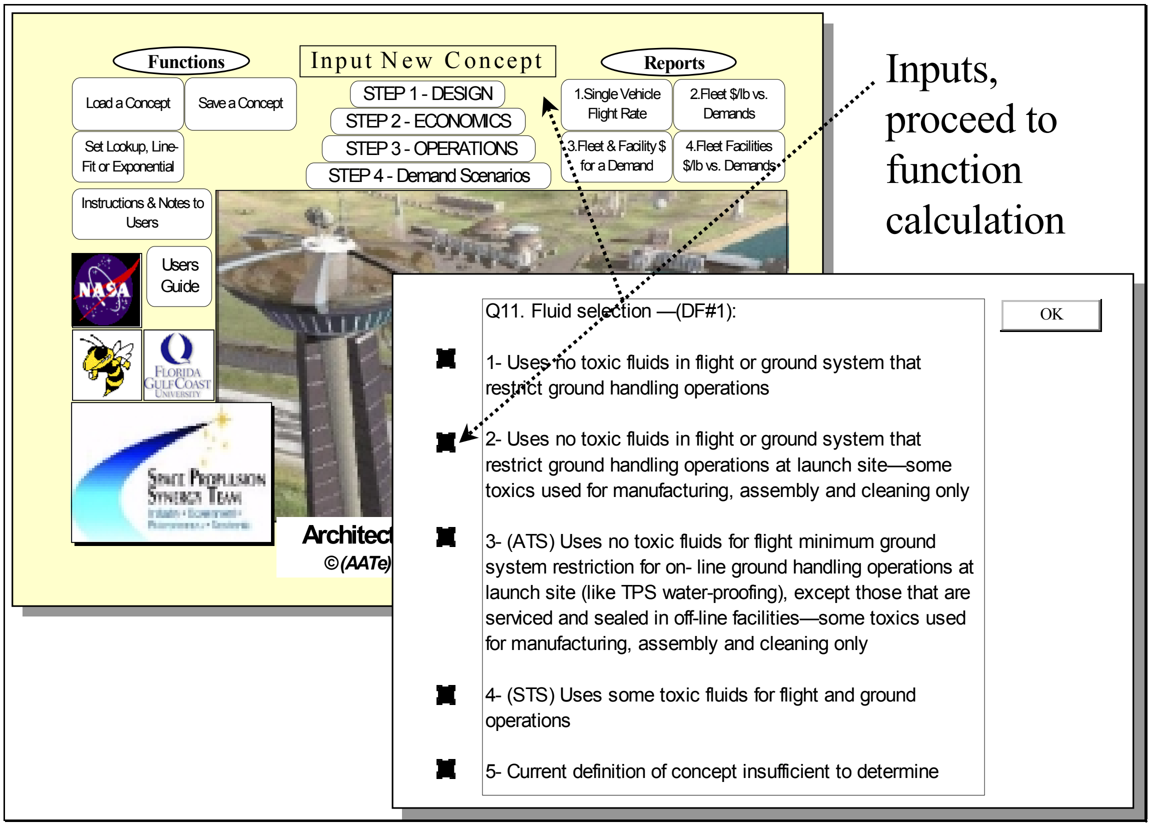

FIGURE 2.0 Sample screens, conceptual definition process

The database serves both as a source of output data as well as a baseline or starting point, in this case using slightly modified Shuttle data from a variety of sources. These sources include an FY 1994 work breakdown structure (WBS) with variable labor, headcount and material costs, the NASA 1991 Zero Base Cost Study, providing insight into fixed operational costs, and historical data providing insight into facility and GSE acquisition costs and major facility flow turnaround times. The value of launch site expertise in filling in gaps is crucial here in interpreting data, extrapolating old data into current numbers, and modifying numbers where reasonable to eliminate the effect of the use of existing facilities, such as the VAB. The objective is to baseline a generic Shuttle, as if clean sheet, where possible, to best extrapolate forward to concepts that may be dramatically improved in capability, innovation and technology.

A sample of the database would be as follows in Figure 3.0 and is modifiable by the user in this model or as data becomes more refined. The degree of improvement in a design, as manifest in the choices made to the input questions, determines the extrapolation forward made by the model and resulting as outputs. Some of these outputs are also shown in Figure 3.0.

In the interest of providing a life cycle perspective, the recurring operations costs/outputs generated by the AATe may be complemented with user inputs for non-recurring factors, such as costs of vehicles, development, or cost of money. In this way the model can be used for gaining a basic life cycle perspective into RLV concepts. Among other outputs, numbers of facilities or vehicles to meet a demand, and costs per pound for certain flights per year for the fleet, lend this insight.

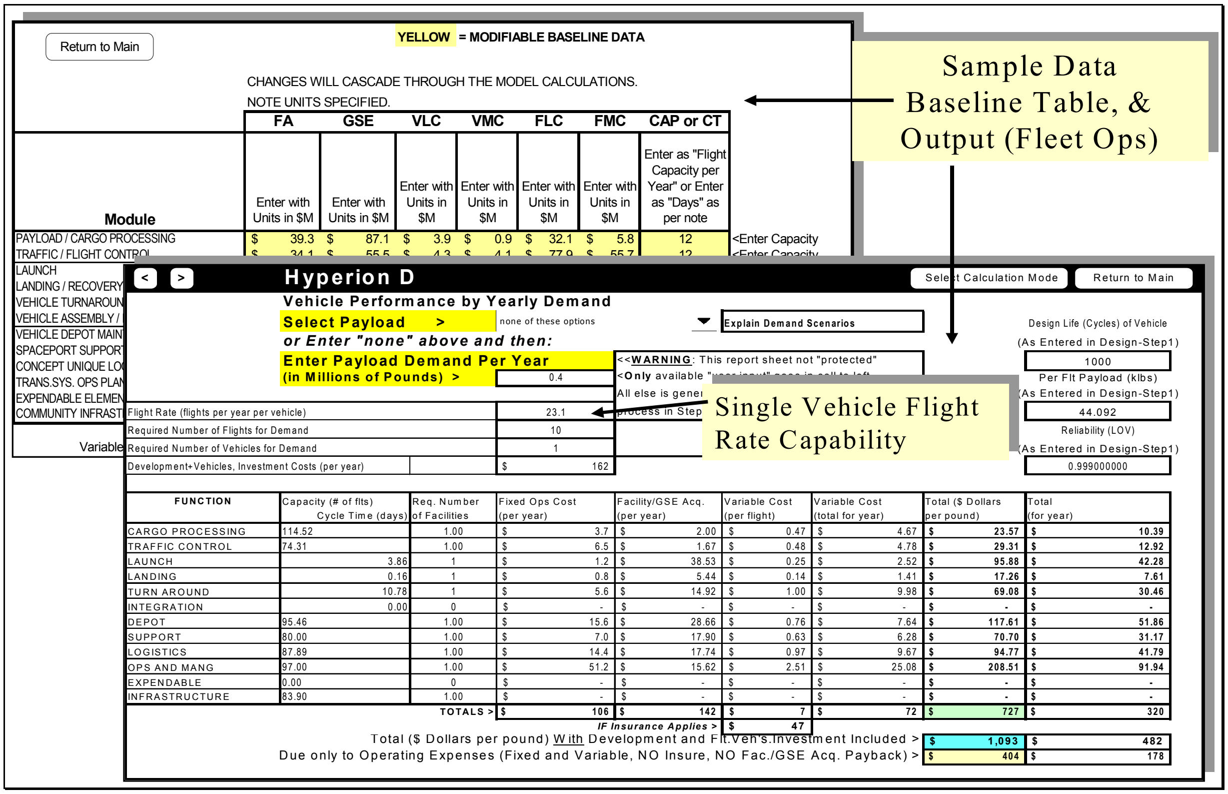

FIGURE 3.0 Sample output sheet report

SINGLE VEHICLE PRODUCTIVITY – KEY CONCEPT

The leap from the multi-attribute utility function to single vehicle outputs occurs based on a series of tables which represent levels of improvement in two major ways from the baseline - improvements in complexity and reliability. Consider that a *perfectly reliable* Shuttle would still be extremely complex. Even if no parts failed during turnaround, the remaining tasks (for example, connecting multiple interfaces, handling multiple elements, hazardous operations, multiple connections that must be broken and verified each flight) would still leave a vehicle unlikely to be anywhere near aircraft like in it's operations or turnaround time. The inverse is also true. Consider a *highly simplified*, highly integrated vehicle, with few different interfaces, or fluids, and with simple preparations for launch. It would, if as undependable as Shuttle hardware, require many removal and replacements of faulty hardware, and also be in no way aircraft like in its operations or turnaround time.

The AATe concept of single vehicle productivity is a cornerstone here. Just as an aircraft has inherent characteristics of reliability, maintainability and overall operational support required, apart from weather it is part of a fleet or not, so too a reusable launch vehicle concept has similar stand-alone characteristics. This model captures design choices, and, after generating an estimation of single vehicle outputs (timelines, single string facility and operational costs, and single vehicle flight rate capability per year), goes forward to calculate fleet operations - multiple vehicles and facilities meeting a yearly spacelift scenario of pounds per year to orbit.

This previous concept, single vehicle productivity, can not be stressed often enough. In many an operations cost modeling exercise, a typical, and flawed, assumption is to model fleets, on the assumption that single vehicle characteristics are non-representative of eventual economics and operations. A further, albeit misinterpreted, assumption is that flight rate drives down costs dramatically and therefore fleets and high flight rates can be skipped to in a model of future RLV operations. This is similar to the assumption that if one vehicle can not produce enough flights at a certain cost, perhaps two will. The result is the elastic set of facilities, which, once chosen, seem to support any flight rate desired and any number of vehicles. The flaw often overlooked is that the single vehicle characteristics must encompass and enable a high flight rate and low cost capability - from the very first vehicle. The amortization of costs, be they for additional vehicles, more infrastructure or increased operations, can not occur quickly without single vehicle characteristics which, besides low cost acquisition, include rapid turnaround at low manpower in minimal facilities. This enables high flight rates at low costs.

The AATe model attempts to capture the effects of both complexity and reliability improvements that together define a future reusable launch vehicle, by building on a strong foundation of operational knowledge gained from Shuttle as well as advanced reusable launch vehicle studies. Together these knowledge bases define to what degree and where improvements need to be applied.

A sample output of single vehicle productivity would be based on 12 such tables as shown in Figure 4.0. Also shown is the determination from the multi-attribute utility function of where the inputted concept is located in the cost table.

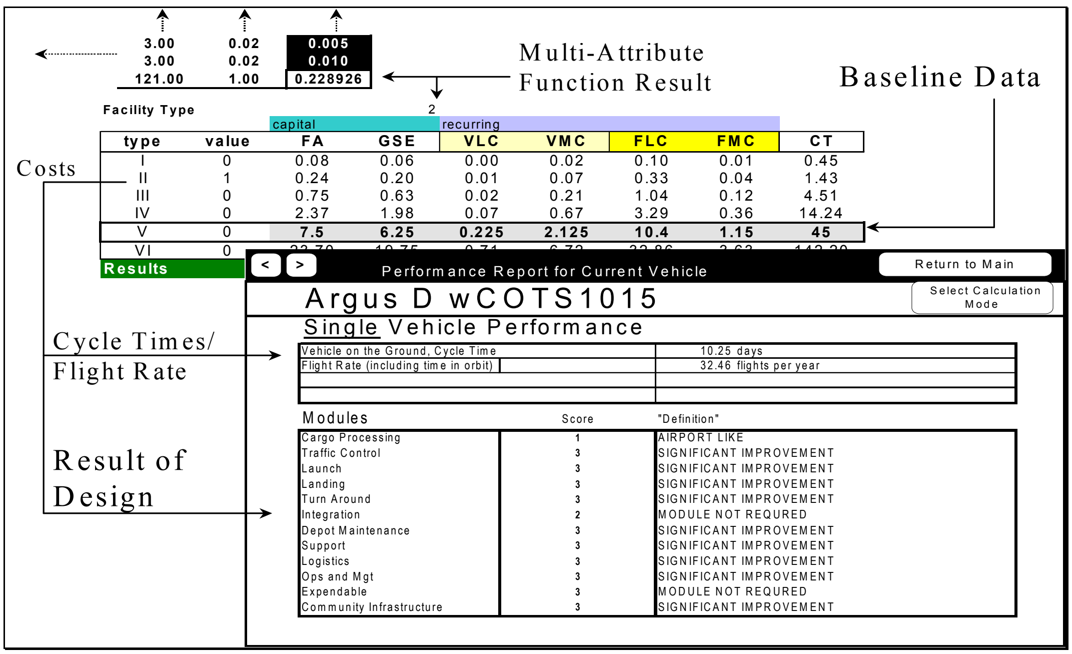

FIGURE 4.0 Sample output sheet relation to databases

CORNERSTONE CONCEPTS

1. The AATe model of spaceport operations revolves around an understanding of SINGLE VEHICLE PRODUCTIVITY as outlined previously.
2. Lack of data down to subsystems levels for Shuttle, combined with a need to explore improvements which occur across sub-system and existing technology boundaries, will make KNOWLEDGE CAPTURE a crucial component of future modeling efforts. This will be so especially until future reusable launch vehicles come on line, not as demonstrators, but as operational systems of vehicles and associated infrastructure, operating in real environments.
3. Operations cost modeling for space transportation is a required MECHANISM OF FEEDBACK between designers and operators. It is therefore necessary to develop models that go beyond the “usual suspects” currently emphasized by operations models - weight and size.

APPLICATIONS

Modeling based on the approach described previously has already been employed in two NASA planning activities. These are the Space Solar Power (SSP) Study and the Space Transportation Architecture Study, 1999 (STAS 99).

These two studies emphasized very different timelines for consideration. The SSP study required about 5 cents per kW-hr delivered to a customer. This is competitive with current terrestrial power supplies. This translated into very ambitious requirements for the space transportation component in this economic scenario. A reverse allocation of about $400/kg to low-Earth orbit (LEO) was arrived at. Further. Flight rates of hundreds per year were required in order that the enterprise place it’s assets in orbit in a timely fashion. Time spent on the ground is time spent accumulating debt and paying investors. Complete systems would have to be built in orbit on the order of 35 million pounds per year to Geosynchronous Earth Orbit (GEO).

In deriving such concepts a previous study, the NASA Highly Reusable Space Transportation (HRST) study was used as a backdrop. This study had already determined the most promising concepts from a qualitative and quantitative review of over a dozen basic types.

The process of further improving the concepts to derive a set of approaches, technology and a design capable of meeting SSP goals was a collaborative one. Multiple design cycles with the concept developers was required. This surfaced both the evolutions required (Figure 5.0) as well as the strengths and deficiencies in the current state of technology and design analysis.

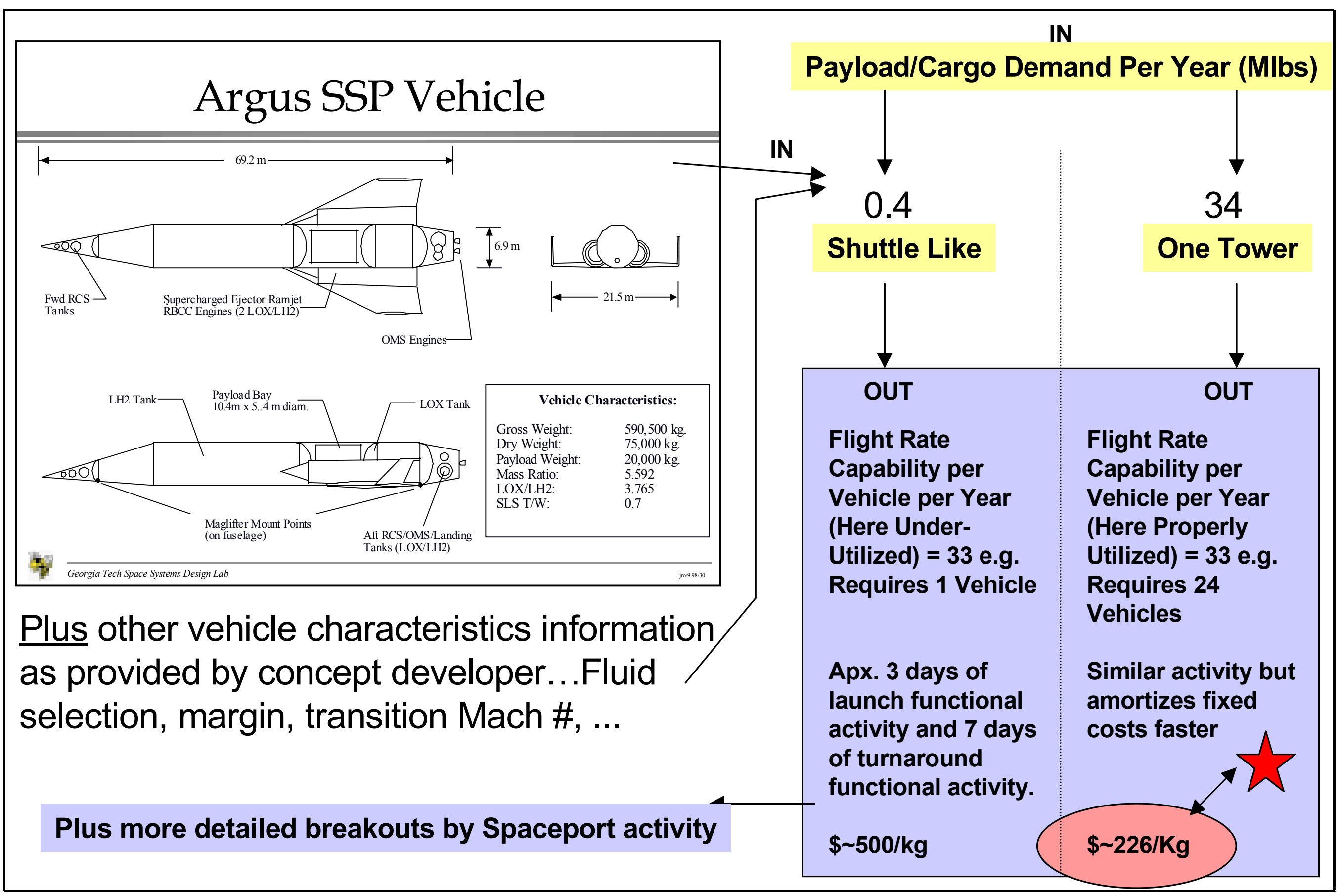

Figure 5.0 Example Inputs and Outputs as Applied to the Space Solar Power Study

Advantages of this analysis process included:

1. The model generated single vehicle productivity, flight rate capability per year per vehicle, and extrapolated outward to fleet implications. The model did not have a flight rate input, avoiding an allocation verification of assumptions already made (no circular logic).
2. Database meets knowledge base. The qualitative turns quantitative.

Weaknesses in the process included:

1. Better insight into the risk of not achieving design objectives is required in the development of technology portfolios based on operations assessments. How likely is it that the TPS will be as robust as advertised? That the systems maturity will be obtained?
2. Better insight into the non-recurring cost of achieving design objectives is required. How much will the extra dependability cost to implement (non-recurring)? How many tests before first flight? How much will each additional "9" cost to achieve?

The ambitious goal of $400/kg was price. Cost was determined to have to be about ½ that in order to generate a profit sufficient to amortize other non-recurring expenses as well as operations. Eventually a Concorde size fleet and flight rate, but at a still higher cost in the low $100/lb would be required. The modeling done here has established that proper sense of direction in systems that are highly integrated, have higher margin, have operations friendly characteristics, and are reliable. They are designed for long life and may essentially be described as expensive airplanes. Nonetheless, independent modeling was done to determine non-recurring cost effects and more tightly integrated modeling is required in the future. Current non-recurring models must better capture the effects of desirable operational variables such as designs for thousands of cycles (versus 100 flight specifications, such as a Shuttle) as well as multiple other reliability and maturity issues.

For STAS 99 similar support was provided to the NASA in-house teams using the modeling of operations described here. This included assessments of only the reusable candidates. Outputs provided included estimating non-recurring spaceport facility and GSE acquisition costs as well as recurring operational costs.

A comparison of various concepts in STAS versus SSP was made. Typical STAS concepts ranked from just slightly less operational costs than Shuttle, to about ½ the costs. Normalization for pounds to LEO assured some equality of analysis.

Of note, any development process often loses payload as projected. A concept may target having 50,000 lbs. of payload only to achieve 40,000 lbs. For this reason, a sensitivity analysis using the design driven model of operations was done for two scenarios to better understand the interactions of variables and the model behavior (Table 3.0).

Scenario 1	Scenario 2
Winged Body, Cylindrical SSTO	Winged Body Cylindrical SSTO
Loses payload in development, from 40, to 30K to LEO, but **loses** most technology high in DDT&E and weight. Results: Flight Rate Capability per Vehicle per Year = 3 (slightly better than Shuttle at 2.4). Need ~ 10 flights, 3 to 4 vehicles in fleet. Costs to place 400,000 lbs. to LEO per year ~ $1,200M recurring.	Loses payload in development, from 40, to 25K to LEO, but **keeps** all design, technology and operability improvements. Results: Flight Rate Capability per Vehicle per Year = 19 (about 8 X better than Shuttle at 2.4). Need ~ 13 flights, 1 vehicle in fleet. Costs to place 400,000 lbs. to LEO per year = ~$200M recurring.

Table 3.0 Loss of payload versus loss of affordability.

The importance of drawing the line on operations improvements versus those driven uniquely by single launch performance parameters (such as payload) is reflected in the model.

NEXT STEPS

The AATe is an implementation of the approach outlined in this paper applicable to advanced reusable launch vehicle concepts operating as sole occupants in an associated, outputted spaceport. The model has been implemented in Microsoft® Excel. The logical and inevitable direction of modeling for operations will be furthered in a project currently in work at the Kennedy Space Center called the Vision Spaceport project. Expendables, reusable vehicles, refinement of the approach, higher user friendliness, mixed fleet operations, and more flexibility in defining an operational concept for a design, are growth areas being addressed by this effort. Areas for future growth that must be considered are the integration of cost models with performance models in a collaborative tool set that reaches from trajectory optimization to the cost of a moldline change.

CONCLUSIONS

The AATe approach is based on knowledge capture, hard data, and the concept of the "spaceport" as an interaction of vehicles and ground infrastructure. It is the efficiency of this interaction that defines this model and generates measures of productivity. If, at some future time, a modeled concept actually comes to fruition, as either a breakthrough or a very expensive endeavor, in the history of RLV's, it will then be seen how closely, or not, one model faired over another in predicting the outcome.

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